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Assessment of the potential of renewables for Brunei Darussalam

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ABSTRACT

This paper presents an assessment for the potential of renewable energy sources: solar, wind, ocean, biomass and hydroelectric for Brunei Darussalam. Long-term measured data of solar radiation, wind energy, ocean waves and rainfall have been used for this project. The assessment criteria for this project were to estimate the availability of renewables that could be harnessed. Despite the large potential for the development of renewables in Brunei Darussalam their exploitation remains insignificant. This study utilized renewable energy supply (RES) assessment software, HOMER (National Renewable Energy Laboratory, US) to compute the utilization of solar thermal energy for domestic and industrial water heating. The modelling results demonstrated that solar thermal energy can adequately and reliably meet the power demand for water heating in domestic as well as industrial applications and it can reduce by substantial amount of the non-renewable of energy consumption used for such applications. Monthly-mean-yearly-averaged amount of global, diffused and direct solar radiation are 18.90, 9.20 and 9.69 MJ m^{-2}, respectively. The theoretical possible annual potential of wave, tidal and offshore wind power is 0.66 GW, 335 kW and 372 MW, respectively. Our preliminary estimates on biomass demonstrate that Brunei Darussalam has a potential to generate 13×10^5 kWh/year.

Contents

1. Introduction

Brunei Darussalam is an oil and gas producing country. Brunei is located between 4°N and 5.8°N latitude and 114.6°E and 115.4°E longitude on the north coast of the island of Borneo in Southeast Asia (see Fig. 1) and enjoys a tropical climate. The humid tropical climate is influenced by two monsoonal regimes; the northeast monsoon predominates from mid December to mid-March, and the southwest monsoon, from mid-May to the end of October. The average annual rainfall varies from a minimum of about 2500 mm on the northeast coast to a maximum of over 4300 mm in the highlands in the extreme south and east. Temperatures are lowest during the northeast monsoon (average maximum 29–30 °C), and reach their highest in the transition period before the onset of the southwest monsoon in May (average maximum 33–35 °C). The population of Brunei Darussalam is estimated at 401,000 the majority of whom are concentrated in the capital, Bandar Seri Begawan, and in the oil-refining area of Seria in the west. The remainder of the country is very sparsely populated and largely

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Fig. 1. Brunei Darussalam(adapted from aesieapgold book [1]).

undisturbed; it consists of mangrove swamps, peat and freshwater swamp forests, and lowland, sub-montane and montanerain forest [1]. It has a total area of 5765 km^2, with a coastline of about 161 km along the South China Sea. The coastline consists of a high-profile sand beach, aligned in a southwest direction along the South China Sea, and a complex estuarine, mangrove and mudflat zone within Brunei Bay in the northeast [2].

Electrical power in Brunei Darussalam is generated by the Department of Electrical Services (DES) under the Brunei Government and by a private company "Brunei Power Management Company (BPMC)". DES has four generating power plants in operation with total installed capacity of approximately 242.5 MW. Three of them are fuelled by gas and one by diesel. BPMC has three power plants with a total installed capacity of approximately 266 MW. The State's power demand is growing at a rapid rate of about 7–10% annually. Household customers account for 38% of electricity usage in Brunei, and represent 63% of customers, while the government accounts for 29% of usage, but only 6% of customers. The oil and gas sector and commercial customers account for 15% and 19% of the electricity usage, respectively. The household, government and commercial sectors are the major users of electricity and this trend is likely to continue [3]. The electricity tariff is regressive in nature, where the more electricity used, the cheaper the cost will be. The tariff is categorized into different sectors, namely: Domestic Tariff; Commercial/Small Industrial Tariff; Heavy Industries Tariff; and Government [3].

In spite of the fact that Brunei Darussalam is an oil and natural gas producing country, the State is diversifying its energy portfolio and intends to go for the global trend in search of alternative renewable energy sources. Electricity prices in Brunei are at well below long-run marginal costs. From the customer perspective, there is little economic incentive to either conserve electricity or to use it more efficiently. This can cause problems when wishing to generate electricity with the use of renewable energy recourses particularly stand alone system for individual uses or for the development of self sustainable energy houses. Without a major technological breakthrough and an innovatory change is social habits, the use of renewable technologies may not make a major impact in society in the foreseeable future.

The State is taking initiatives in exploiting renewable energy resources as an alternative and sustainable means for power generation to alleviate high dependency on oil and natural gas. The aim of this article is to explore the potential of renewables namely solar, wind, hydroelectric, ocean and biomass as an alternative to conventional fuels that have many benefits like energy resource diversification, decreased fossil fuel use, and reduces per unit greenhouse gas (GHG) emissions.

2. Potential of renewables

An energy resource that is naturally replenished and its supply is not affected by the rate of consumption is known as a renewable energy source. Examples of renewable energy sources are solar, wind, tidal, geothermal, biomass, hydroelectric and ocean energy. Renewable energy technologies contribute a small but rapidly growing and sustainable role in the world's energy scenario. Many researchers [4–29] have presented valuable research findings on the role of renewable energy technologies as future inexhaustible energy generation resources.

2.1. Solar energy

Solar radiation is the driving force for the different types of renewable energy technologies. The worldwide potential for direct use of solar technology (solar thermal and photovoltaic) and indirect manifestation of solar radiation by means of wind energy, hydroelectric, ocean energy, biomass have been extensively studied [30–34] and used in different parts of the globe.

Brunei Darussalam is located in the sunbelt region of the globe and receives a substantial amount of solar radiation that makes it an ideal place for the application of solar energy technologies. The State has four districts: Belait, Brunei/Muara, Temburong and Tutong. The geographical locations of these districts are given in Table 1.

One of the important requirements for the design of any solar energy conversion equipment/device is information on the amount

Table 1
Geographical locations of the four districts of Brunei Darussalam.

District	Latitude (North) (°)	Longitude (East) (°)
Brunei/Muara	4.90	114.95
Belait	4.30	114.68
Temburong	4.62	115.18
Tutong	4.78	114.50

of solar radiation and its components at a given location. There are three components of radiation reaching at ground: direct radiation, diffused radiation and global radiation. Meteorological Departments usually measure global and diffused components of radiation and the direct component is estimated. The amount of measured and estimated global solar radiation over Brunei Darussalam is shown in Fig. 2.

Five consecutive years measured data collected from the Meteorological Department of Civil Aviation, Ministry of Communication, Brunei Darussalam was used to estimate the amount of solar radiation for the four districts in the State. The data presented in this figure demonstrate that the monthly-averaged amount of global radiation lies in the range of 17.46–20.88 MJ m^{-2} throughout the calendar year. The bright sunshine hours are in the range of 6.97–8.47 h/day and the diffused radiation over the country ranges from 8.57 to 9.73 MJ m^{-2} in a calendar year [35,36]. The use of solar radiation to heat a working fluid (water or air) is the basis of solar thermal systems. Though a variety of solar thermal devices are feasible at present the most frequently used are solar water heaters, dryers and cookers. The performance of a solar collector is highly influenced by its orientation and its angle of tilt with the horizontal. A mathematical model was used for estimating the optimum tilt angle for Brunei Darussalam by maximising the global radiation. The optimum tilt angle for Brunei Darussalam was computed as 3.3° with the horizontal and orientated towards the equator i.e. towards south [37]. The data presented reveal that the solar energy technologies have potential to be used as an alternative means of energy production/generation in the country. A number of research and development projects have been conducted on solar thermal and photovoltaic technologies and their findings indicate that both solar thermal and photovoltaic technologies can play an important role to reduce the dependence on fossil fuels for power generation in the country [38–40].

A box type solar cooker was developed and tested in the Department of Physics, University of Brunei Darussalam and the interior temperature of the cooker without any load with reflectors reached 130 °C. A temperature of 100 °C was attained without any reflector. A number of different local dishes were cooked which included rice, fish, vegetables, potatoes, eggs and cakes. The maximum interior and cooking pot temperatures recorded were in the range of 89–98 and 87–98 °C, respectively. An experiment to heat water was also conducted and a maximum temperature of 85 °C was recorded. This result demonstrated that solar thermal energy can be used for cooking, also it has potential to be used for domestic water heating as well as for commercial applications [41]. The renewable energy supply (RES) assessment software, HOMER (National Renewable Energy Laboratory, US) was used to design solar water heaters for domestic and industrial uses [42]. It was noted that a solar water heater supplying 400 l of water daily with a temperature of 40 °C needs 4 units of solar thermal collectors with a size 1 m^2 each. With the use of this water heater 20 MWh energy can be saved over a year in Brunei [43].

Solar dryers use solar radiation to heat air that is used to remove moisture from material placed inside the enclosure. The most popular solar dryers are cabinet type and the solar green house. Solar dryers have the potential to be used for drying fish, vegetables, crops and fruits that are very popular in Brunei Darussalam. The development of a solar thermal industry in the State would be highly beneficial for popularising this technology as well as being as income generating option.

The Government of Brunei Darussalam is very keen to explore energy generation using photovoltaic technology. In August 2008, Brunei Darussalam and Mitsubishi Corporation (Japan) signed a Memorandum of Understanding to construct a large scale photovoltaic (PV) demonstration project known as "Tenaga Suria Brunei". The PV system with a nominal capacity of 1.2 MW is being installed at Seria Power Station in Belait District. The commissioning of this system is expected to be completed at the end of the year 2010. It is anticipated that this PV power station will generate electrical energy of approximately 1344 MWh/year that can save the amount of crude oil equivalent to approximately 340 kl/year and cut down the emission of 940 ton of CO_2 per year.

As Brunei Darussalam is located in the equatorial region of the globe a significant amount of electricity is used to cool buildings all over the State that is growing rapidly over the years. Buildings are

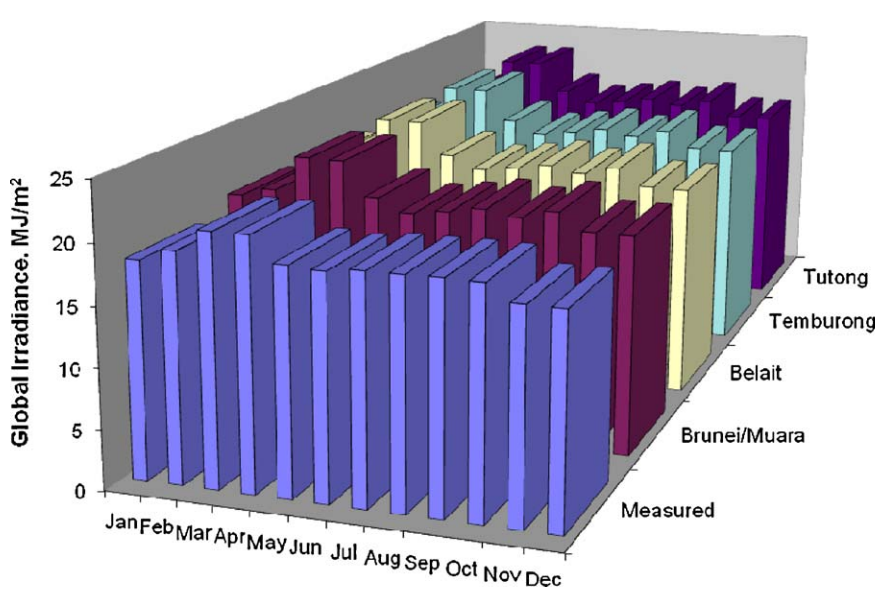

Fig. 2. Measured and estimated annual global solar irradiance over Brunei Darussalam.

not designed on the principles of energy efficiency and energy management and a substantial amount of energy is wasted. It is highly desirable that buildings would be designed on passive architecture technology to cut down the energy waste.

2.2. Wind energy

The potential of wind energy is temporal as well as spatially dependent. This variation is not only caused by the resource characteristics but also by geographical, techno-economic and institutional factors which can only be approximately quantified. This leads to the need of an assessment of long-term measured data supported by mathematical modelling to examine the feasibility of such a diffused source of energy. In past, several estimates of worldwide potential for wind energy have been made [44,45] using different regional aggregations by exploiting only technical rather than the economical aspects. de Vries et al. [46] conducted the feasibility and presented a new assessment model for the prediction of the future costs and technical potential of electricity from onshore wind as well as from other renewable resources. Their findings indicate that wind power would be the most interesting among the three most important renewable and sustainable energy option namely wind, solar and biomass (WSB) to produce electricity. They also concluded that wind power would be able to produce electricity at somewhat lower costs in 2050 than biomass.

In the present project five consecutive years' data (2004–2008) on surface wind have been used. The hourly surface data were collected with a computer controlled system using an anemometer situated at 10 m above the ground. The data have been compiled and analysed using the Wind Energy Resource Analysis (WERA) software [47] and the results obtained revealed that the mean surface wind speed over a period of 5 years was 2.1 ms^{-1} indicating that wind power using surface wind in Brunei Darussalam is not a viable option. The offshore wind would provide adequate wind resources for wind farm development. The offshore wind data for a period of 6 years (2003–2008) that was collected by an automated computer controlled system on 1-min interval. WERA software package was used to analyse the raw data. The results were obtained on the energy density (E_D), energy intensity (E_I), the most frequent wind velocity (VF_{max}) and the velocity contributing the maximum energy (VE_{max}). The monthly-mean values of these parameters that are averaged over a period of 6 years are presented in Table 2.

The results tabulated in Table 2 demonstrate that the State has adequate offshore energy resources to be harnessed. The theoretical possible monthly-mean-yearly-averaged offshore wind energy density is 77 W m^{-2}. The offshore wind energy turbines are usually installed approximately 30 m off the coast that corresponds to the region of shallow water. The area for offshore wind generation in Brunei Darussalam would be 483×10^4 m^2 based on the coastline of 161 km and the theoretical possible potential is 372 MW per annum.

Table 2
The monthly-mean values for E_D, E_I, VF_{max} and VE_{max} averaged over 6 years (2003–2008) using offshore wind data.

Month	E_D (W m^{-2})	E_I (kWh m^{-2})	VF_{max} (ms^{-1})	VE_{max} (ms^{-1})
January	130	94.78	3.83	7.66
February	110	79.67	3.61	7.23
March	60	47.03	3.03	6.06
April	40	28.08	2.55	5.11
May	50	37.70	2.82	5.63
June	60	45.56	3.00	6.00
July	70	47.77	3.05	6.09
August	70	51.23	3.12	6.24
September	80	60.81	3.30	6.61
October	80	59.50	3.28	6.56
November	60	47.40	3.04	6.08
December	110	81.8	3.65	7.29

2.3. Ocean energy

The oceans that cover approximately 71% of the earth's surface are a huge solar thermal collector and hold an enormous amount of untapped energy. The ocean energy is renewable, continuous throughout the year and pollution free. The geographic location of Brunei Darussalam makes it possible to look into the potential of ocean energy. Brunei Bay consists of an area of about 250,000 ha, shared between Brunei Darussalam and the East Malaysian States of Sarawak and Sabah. The outer bay varies in depth from about 20 to 40 m; the inner bay is generally less than 5m deep [1]. The ocean is a huge storage of natural energy of the following forms:

- Ocean Thermal Energy Conversion (OTEC)
- Wave energy
- Tidal energy

An extensive research has been conducted to harnessed ocean energy [48] and a few of these forms have undergone limited commercial development. Literature states that the marine and tidal energies have a global potential of 5 TW [49]. Muetze and Vining [49] reported that there is approximately 8×10^3 to 80×10^3 TWh/year of wave energy in the entire ocean and wave energy provides "15–20 times more available energy per square meter than either wind or solar".

2.3.1. Ocean Thermal Energy Conversion (OTEC)

The vertical temperature distribution in the open ocean constitutes two layers separated by an interface. The surface layer is warmed due to the absorption of solar radiation and mixed to deep water by wave motion. The bottom consists of colder water. The temperature difference between the warm surface ocean water and the cold deep ocean water is equal to or greater than 20 °C. Thermodynamically this implies that there two enormous reservoirs providing the heat source and heat sink required for a heat engine to work. The heat engine can be designed to transform the thermal energy into electricity. This is referred to as OTEC.

There are two types of OTEC systems. First is the open cycle system that uses sea water as the working fluid. In this system, the warm surface water is flash-evaporated in a chamber maintained under high vacuum and the generated vapour is utilized to drive a low pressure turbine connected to the generator. The exhaust stream is condensed using cold sea water. The closed cycle system utilizes a low boiling point fluid like freon or ammonia as the working fluid. The fluid is evaporated using the warm surface sea water. After the vapour drives the turbine, it is condensed by cold sea water and pumped back to repeat the process [50]. Vega [51] claimed that however several techniques have been proposed to harness OTEC but the closed cycle and the open cycle systems have a solid foundation of theoretical as well as experimental work. The author reported that the economic evaluation of OTEC plants indicates that their commercial future lies in floating plants of approximately 100 MW capacity for industrialized nations and smaller plants for small-island-developing-states (SIDS).

Nihous [52] presented worldwide assessment of OTEC resources and claimed that 3–5 TW of electrical power could be generated. Odum [53] proposed a land-based OTEC system for Taiwan using energy evaluation methods. Moore and Martin [54] developed a nonlinear, nonconvex minimum area targeting formulation for the analysis of ocean thermal conversion systems. The authors demonstrated this methodology in an OTEC case study, using ammonia as a working fluid, in which the power generated was used to derive PEM electrolyser for hydrogen production. Straatman and

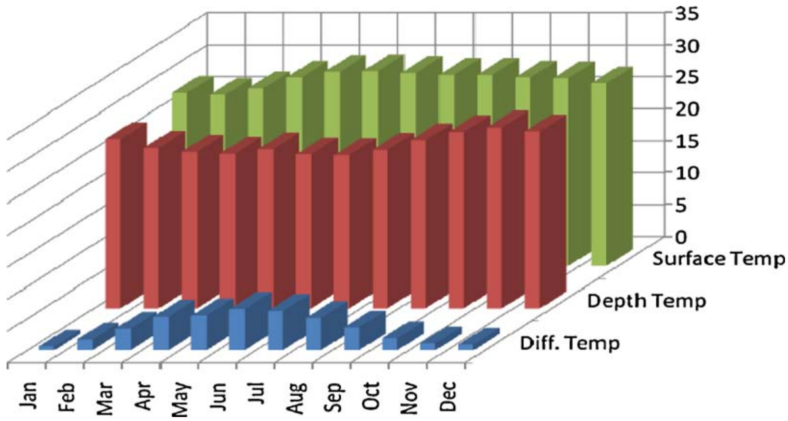

Fig. 3. Monthly-averaged measured temperature (°C) at surface and bottom layers of ocean and temperature difference between these two layers in Brunei Darussalam.

van Sark [55] proposed a new hybrid design of an OTEC system with an offshore solar pond: OTEC–OSP. They claimed that a floating offshore solar pond to an OTEC system increases the temperature difference in the Rankine cycle resulting in an improved efficiency of 12% compared to that of a typical OTEC system of 3%. This higher efficiency results in much lower investments needed for power blocks, while the OSP is fabricated using very low-cost plastic foils. The authors also claimed that the new proposed OTEC–OSP design can be located in many sunny coastal areas in the world.

Six consecutive year data (2003–2008) on surface and bottom temperatures of Bruneian ocean have been used to evaluate the potential of OTEC for Brunei Darussalam. The data were collected on an hourly interval using a 300 kHz Acoustic Doppler Current Profiler (ADCP) by Telednye RD Instruments Marine Measurements. The surface temperature of ocean water lies in the range of 26.8–30.5 °C throughout a calendar year. The temperature difference between the surface and the bottom layers of ocean water averaged over a period of 6 years for Brunei Darussalam is shown in Fig. 3. The data presented in this figure demonstrate that temperature difference ranges from 1 to 6.5 °C. The small temperature difference is due to the shallow ocean around Brunei Darussalam. Literature states that the minimum temperature difference required for an economically viable OTEC conversion would be at least 20 °C [56]. Since the vertical oceanic temperature difference for Brunei Darussalam is less that 20 °C, therefore, OTEC conversion is not economically viable as an alternative energy source for the State.

2.3.2. Wave energy

The Sun radiation is absorbed by the land's surface, ocean and atmosphere that raise their temperatures. The uneven heating of the earth's surface by the Sun causes the wind. Approximately 1.5% of incoming solar radiation is converted into wind. Ocean waves arise by the action of the wind on the ocean surface which is a source of energy that is continuously being replenished. Ocean waves carry a tremendous amount of energy and it can be extracted directly from the surface motion of ocean waves or from the pressure fluctuations below the surface. The potential of wave energy is not uniformly distributed over the globe but it is dependent on the geographical location, time of day, month of year and from season to season.

The potential of wave power per meter of wave front (P) in shallow water like Brunei Bay can be estimated using the following equation:

$$P = \frac{1}{16\pi}\rho g^2 H^2 T = 0.5 H^2 T_z \quad \text{kW} \quad \text{m}^{-1} \tag{1}$$

where ρ, g, H, and T_z are the density of sea water (1027 kg m^{-3}), gravitational constant (9.81 ms^{-1}), wave height (m), and zero-crossing period (s), respectively.

However, the actual power derived from ocean waves is considerably less than that given in Eq. (1) but this may be considered as a convenient unit for determining the potential of ocean wave energy at a location. The accuracy of the measured data and its availability for computation of such calculations plays an important and a crucial role for feasibility studies. A comprehensive description of developments in wave forecasting has been reported by Janssen [57]. The author discussed the role of ocean waves in the transfer of momentum at the air–sea interface. He claimed that as the waves break their energy is dumped into the ocean column and it helps in the ocean circulation. The ocean waves are also affected by the surface currents. Therefore, the author proposed that ocean wave and ocean circulation models would be coupled to develop a single model for the geosphere and such a model has already been used in seasonal forecasting system at European Centre for Medium Weather Forecasting, UK. Reikard [58] used time-series mathematical models to predict the wave energy flux. Hourly and daily ocean wave data was used for this analysis. The author reported the range of errors in these data sets is 17–25% at an hourly interval and 28–41% at a daily intermission, which are relatively high. He related such high errors with the need of backup sources of power in order to compensate for the statistical nature of ocean waves. Missing data is another important factor for an accurate computation of the availability of ocean wave energy and it is very common at the majority of the observatories over the globe. Özger [59] proposed a neuro-fuzzy approach to overcome the missing data on significant wave heights with the use of data on this parameter of neighbouring stations that exhibits similar features.

A variety of ocean wave technologies have been used to convert wave energy into electricity that includes nearshore, offshore and farshore. All these technologies have one common feature that these should be installed at or near the water surface. The difference would be in their orientation to the waves with which they interact and the manner in which they convert the energy of the wave into electricity. The most commonly used wave power devices can be characterized as [60]:

- Buoyant moored devices consisting of a floater that is moved by the waves. This movement may be either up and down or around an axis. The energy can be extracted from this motion.
- Hinged contour devices have several floaters that move when a wave passes. The motion of these floaters is related with each other leading to the extraction of energy mostly with hydraulic pumps.
- Oscillating water columns comprising of chambers in which water level rises and falls as an ocean wave progresses and its crests and troughs pass through. The change in the water level inside the chamber allows air to come into and go out of

this chamber that derives a well turbine connected to a generator.

- Overtopping devices are low head hydro systems. Ocean waves are channelled toward a central collection basin leading to a rise in the volume of water that spills over a retaining wall to fill the basin. This gives a small elevation differential with the surrounding water level that can be exploited using a standard low head hydro turbine.

Ocean wave technologies are still in the development stage. However, a number of researchers over the globe have been conducting intensive research to improve and optimize wave power devices but still no clearly superior engineering solutions established. Agamloh et al. [61] designed and tested a new rotary direct-driven ocean energy extraction system. The device employs a contact-less force transmission system (CFTS) to couple a float to the power take-off (PTO) mechanism made up of a ball screw, unidirectional clutch and a permanent magnet generator. The system was successfully tested in irregular waves in a flume but it is still under investigation for a comprehensive linear test bed. Ivanova et al. [62] have simulated a directly driven permanent magnet linear generator for a site near Shannon in the southwest of Ireland. The site has large waves with 5 m amplitude and 11 s period, with high energy density equal to 68 kW m^{-1} potentially available. The simulation results of the system are encouraging and show economic and technological possibilities to construct and exploit the converter. Elwood et al. [63] presented an overview on the SeaBeavl project and reported on the ocean testing of a 10 kW direct-driven wave energy conversion system. It is documented that this project helped to improve the testing procedures for wave energy devices and gave the researchers valuable experience on the ocean. Leijon et al. [64] discussed an electrical approach to wave energy conversion and highlighted that the raw power be rectified into DC voltage and DC/AC converter suited for correct voltage for grid connection be implemented. Because studies reveal that the DC voltage at different wave climates plays an important role in the optimization of the whole electric production system. Wolfbrandt [65] presented a systematic approach for automated design of a longitudinal-flux permanent-magnet machine (LFM) with a rectifier, using time-stepping finite-element analysis, where the piston is driven by a buoy. He claimed that there is a good agreement between the models with constant and sinusoidal speed. Özger and Sen [66] discussed the statistical behaviour of wave energy that directly affects the wave power level variability. These authors computed the return period and risk calculations for ocean energy applications. They also claimed that the return period can be up to 23% improved and the risk can be 11% smaller than conventional estimates, which means that the expected design life of a system becomes longer and risk is reduced with the consideration of persistence. Iglesias et al. [67] computed the wave energy potential in Galicia, Spain based on 3-hourly data for a period of 10 years (1996–2005) by employing a third generation ocean wave model. They reported that the total energy was found to range from 128.59 to 438.89 MWh m^{-1} in an average year, whereas the average wave power varied between 14.68 and 50.10 kW m^{-1}.

Six years data on maximum height (H_{max}), significant height (H_{sig}), peak spectral period of total spectrum (T_p) and mean zero-crossing period (T_z) have been used to investigate the potential of wave energy for Brunei Darussalam. The maximum wave height is the largest individual wave within the averaging period. It is defined as the greatest vertical distance between a wave crest and its succeeding trough. H_{sig} is four times the standard deviation of the sea surface over the averaging period and is approximately equal to the average of the one-third highest waves. Wave data were sampled at 0.5-s intervals. All wave parameters were calculated from spectral analysis of 4096 data points (34 min, 8 s) and with updating every minute. Heights are measured in meters and periods in seconds. Eq. (1) has been used to estimate the potential of wave energy for Brunei Darussalam. The results obtained, monthly averaged, taken over a period of 5 years are tabulated in Table 3.

Table 3
Monthly-mean ocean wave power that is averaged over a period of 6 years using measured data (2003–2008) available to be harnessed in Brunei Darussalam.

Month	Power (kW m^{-1})
January	467
February	314
March	185
April	54
May	88
June	67
July	114
August	122
September	129
October	151
November	270
December	487

Results presented in this table demonstrate that the potential of ocean wave power varies throughout a calendar year. The maximum monthly-averaged power than can be generated from ocean waves in Brunei Darussalam is in the month of December which is 487 kW m^{-1}. The minimum monthly-averaged power corresponds to the month of April that is 54 kW m^{-1}. It has been noted that potential of wave energy in the months of April–November is less compared with the other months of a year. The length of the coastline of Brunei Darussalam is approximately 269 km that indicates that ocean waves could produce 15–126 GW. The annual theoretical potential of the wave energy is 66×10^{10} W.

2.3.3. Tidal energy

Tidal energy is due to the mutual gravity interaction between the Earth, Sun and Moon. Periodic change of water levels and associated tide currents are due to the gravitational force that is dependent on the distance between two bodies leading to its differential variable nature. The magnitude of the tide at a given location is due to the relative position of Moon and Sun with respect to the Earth, rotation of Earth and the geographical location and shape of the sea and coastlines. As this energy is due to the mutual gravitational interaction among three bodies and is inexhaustible, therefore, it can be classified as a renewable energy source. This energy can be extracted with the use of tidal energy generators. The stronger the tide is the greater is the potential for tide energy generation. As the Moon is near to the Earth compared with the Sun indicating that the mutual gravitational affect due to the Moon on the Earth and vice versa is stronger. The daily flexing of the earth causes loss of energy due to the Earth's rotation. This energy goes into heat, increasing the Earth's temperature. The loss of rotational energy means that the Earth is slowing down in its rotation. It is stated in the literature that during the last 620 million years the period of rotation has increased from 21.9 to 24 h. In this period the Earth has lost 17% of its rotational energy. The tidal power may take additional energy from the system leading to an increase in the rate of slowdown. But the effect would only be noticeable over millions of years, thus being negligible [68].

It has been reported that tidal power can be harnessed in two different ways [68]:

- Tidal stream systems utilize the kinetic energy of moving water to power turbines at a lower cost compared to barrages.
- Barrages make use of the potential energy due to the difference in height between high and low tides. Barrages are dams across a

tidal estuary that require a high construction cost. Sometimes tidal power cannot be harnessed due to the lack of a viable site for the barrage.

Ilzarbe and Teixeira [68] reported on the patents related to power generating apparatus suitable for use in extracting energy from the tidal movement of water. They highlighted the significance and limitations of the patents reviewed. Seim et al. [69] discussed tidal circulation and energy dissipation in a shallow, winding estuary. The authors presented an analysis of moored times series and showed that a transition in the character of the tidal wave as it enters the estuary, changing from a near standing wave on the continental shelf to a more progressive wave on the estuary.

The average power from a tidal barrage can be computed using the following equation:

$$\bar{P} = \frac{\rho A g R^2}{2\tau} = \frac{5.04}{\tau} = 0.056AR^2 \quad (2)$$

where ρ, A, g, R, and τ are the density of sea water (1027 kg m^{-3}), area of tidal barrage (m^2), gravitational constant (9.81 ms^{-2}), tidal range (m), and tidal period (h), respectively. There is one low and one high tide each day in Brunei Darussalam that corresponds to a tidal period of 24 h and 25 min.

Garrett and Cummins [70] conducted research on the power potential of tidal currents in channels. They developed a mathematical model to evaluate the available tidal power that can be converted into electricity. Their model assumes that turbines are deployed in uniform fences, with all the water passing through the turbines at each fence and ignores losses associated with turbine operation and the back effect on the forcing of changes in the channel flow. They presented an equation to compute the maximum average available power which is dependent of the peak volume flux (Q_{max}) in the undisturbed state:

$$\bar{P} = 0.21\rho g A Q_{max} \quad (3)$$

Takikawa et al. [71] estimated tidal currents in the Tsushima straits using long-term Acoustic Doppler Current Profiler (ADCP) observations. They reported that the contributions of the tidal currents to the total kinetic energy and the mean eddy kinetic energy averaged along the ferryboat track are 0.56 and 0.71, respectively, suggesting that tidal current activities are generally more dominant than the mean current activities and much more dominant than eddy activities. The only region where the eddy activities are comparable to the tidal current activities is located east of the Tsushima island which is downstream of the Tsushima warm current. Grabbe et al. [72] reviewed the tidal current energy resource in Norway. They reported that the geographic and

Table 4
Monthly-averaged range of low tide, high tide, range of tide and tidal power available to be harnessed in Brunei Darussalam. The averaged is taken over a period of 6 years (2003–2008).

Month	Low tide (m)	High tide (m)	R (m)	P (W m^{-2})
January	0.03	2.17	2.14	0.26
February	0.07	2.00	1.93	0.21
March	0.19	1.78	1.59	0.14
April	0.18	1.89	1.71	0.16
May	0.07	2.05	1.98	0.22
June	0.03	2.15	2.12	0.25
July	0.04	2.16	2.12	0.25
August	0.12	2.09	1.97	0.22
September	0.3	1.92	1.62	0.15
October	0.36	2.03	1.67	0.16
November	0.21	2.18	1.97	0.22
December	0.09	2.24	2.15	0.26

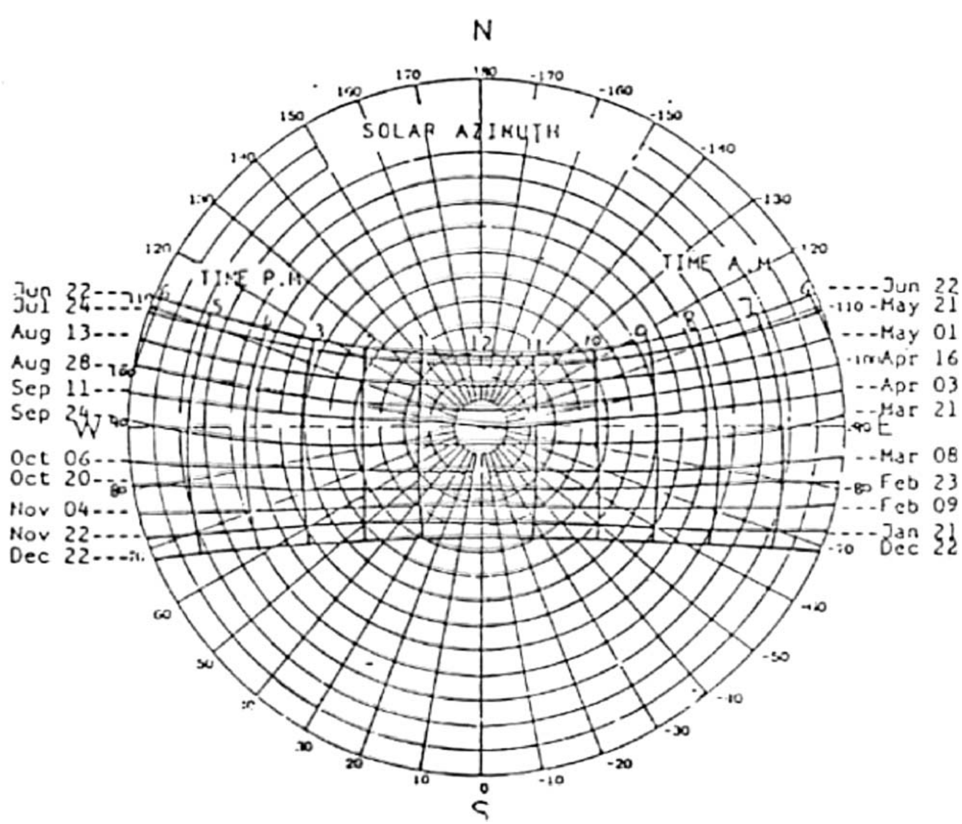

Fig. 4. The apparent motion of the Sun over Brunei Darussalam(adapted from [75]).

oceanographic conditions make Norway an ideal location for tidal power generation. More than 100 sites in Norway were identified yielding a theoretical resource of the order of 17 TWh. It was noted that due to the complex coastline of Norway, it is likely that there are many more sites that could be considered for tidal power generation. They further added that Norway possess a palpable tidal energy resource, although assessments to date of its extent are incomplete. Brooks [73] and Canhanga and Dias [74] examined the potential of tidal energy for Passamaquoddy-Cobsook Bay and Maputo Bay, respectively. The reported findings indicate that Passamaquoddy-Cobsook Bay has a potential of 10 kW m^{-2} while tidal heights and currents for Maputo Bay revealed that there are no maximum fluxes of energy for this bay.

Six years data on tides for Brunei Darussalam were used to explore its potential for the State. Results presented in Table 4 were obtained using Eq. (2) demonstrating that a very small tidal power in the range of 0.14–0.26 W m^{-2} is available. This is because of the fact the Brunei is located in the equatorial region of the globe where the tidal effect is minimal. The pattern observed in the amount of available tidal energy over the country is notable. The observed pattern can be divided into six groups which are: January and December; February and November; March and October; April and September; May and August; and June and July. This grouping is not by chance but it reflects the relative motion of the Sun and the lunar cycle over Brunei Darussalam. The relative motion of the Sun over the State is shown in Fig. 4 that explains these six groups. Only three groups January and December; June and July; and May and August give the same amount of energy in both months in a group while in the rest of the three groups a small variation in available energy has been noted. These small variations in tidal energies may be due to the difference in the rotation period of the earth around the Sun and the lunar cycle coupled with their mutual gravity interactions.

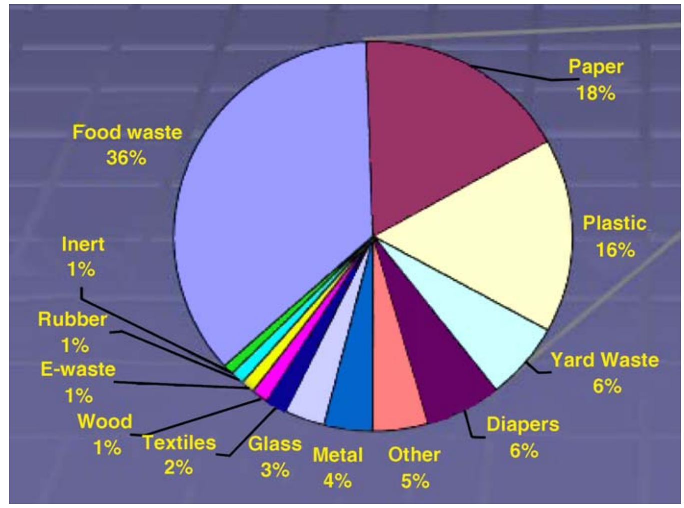

Fig. 5. Municipal waste composition of different materials in Brunei Darussalam(adapted from [76]).

Results presented in Table 4 reveal that annually 2.08 W per unit area tidal energy can be generated. Brunei has a coastline of 161 km and theoretically there is a potential of approximately 335 kW per annum.

2.4. Biomass

Biomass is the organic matter from plants, animals and solid waste and can be classified into two categories:

- Agriculture crops and forests.

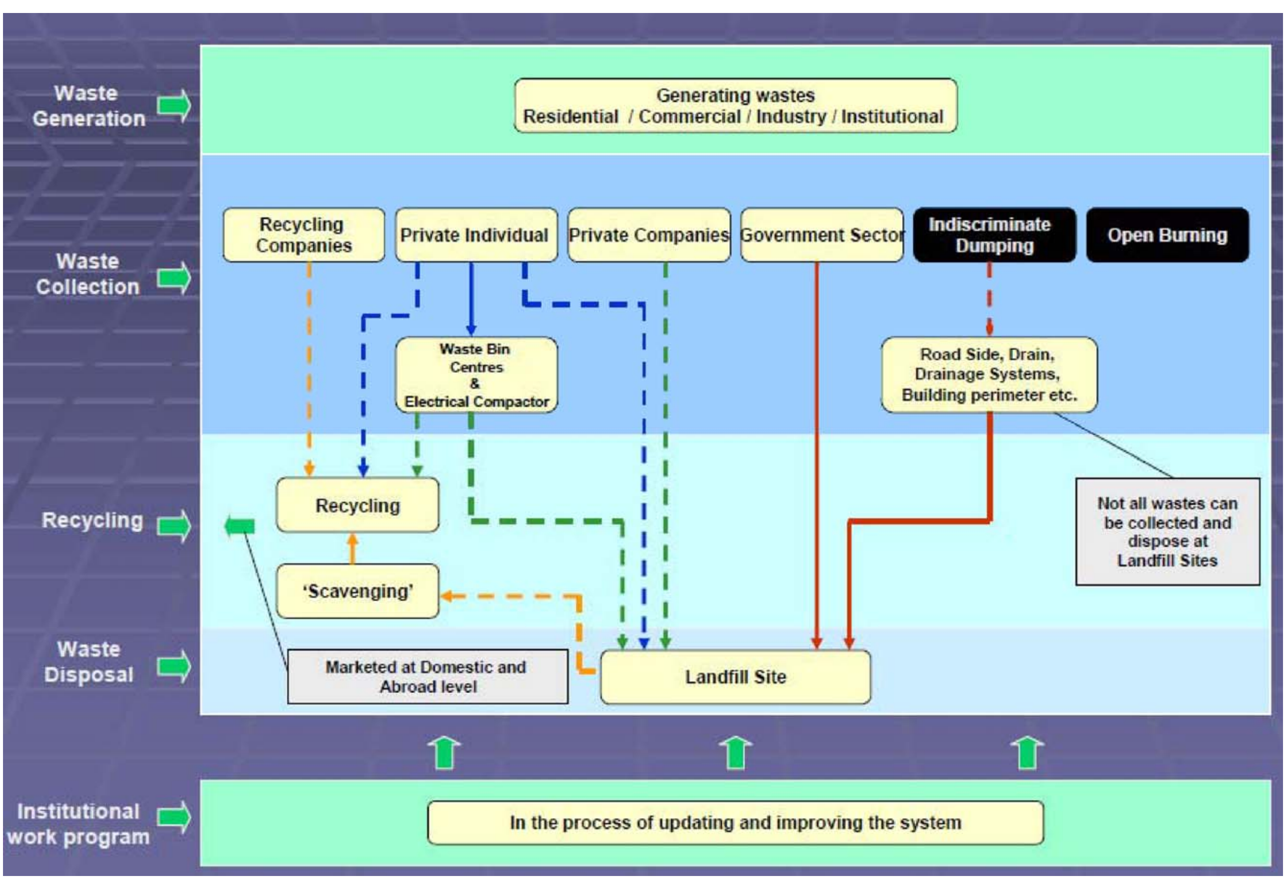

Fig. 6. Existing waste management system in Brunei Darussalam(adapted from [76]).

- Solid Wastes like municipal wastes, animal residues, forest and agriculture wastes, bioprocess wasters, paper wastes, food wastes, etc.

Brunei Darussalam imports 80–85% of its food requirements. However, trends are changing and cultivation of rice has started with the theme to become self reliant in this crop. In addition, other crops have been grown for local consumption that includes sweet potato, banana, cassava, coconut, pineapple and vegetables. The other important source of biomass is solid wastes. It has been reported that the waste disposal per capita is 1.4 kg per person per day leading to an annual average waste of 189,000 ton [76]. The author has highlighted the distribution of different waste materials in Brunei Darussalam that is shown in Fig. 5.

There are six landfill sites in the State, one is located in Brunei/Muara, two in Tutong, two in Belait and one in Temburong districts. Brunei Darussalam has excellent door to door waste collection facilities at domestic, industrial, institutional, commercial, the Government buildings, restaurants and hotels. In addition to these services, Government has also provided public waste material collection sites distributed throughout the country to encourage the public to dispose of their waste at these locations from where it is transported to the nearest landfill site. The existing waste management system is shown in Fig. 6

Literature states that one million tons of solid waste in a landfill can produce an energy equivalent to 7×10^6 kWh/year that can power 700 homes [77]. The annual average solid waste of Brunei Darussalam capable the country to produce energy from its solid waste equivalent to 13×10^5 kWh/year and can provide power to approximately 130 homes.

Research and development projects at the University of Brunei Darussalam and the Institute of Technology of Brunei Darussalam are underway to generate landfill gas from the solid waste in the State. Landfill gas technology can not only provide fuel, but is also important for comprehensive utilization of solid waste, development of agriculture economy in general and rice production in particular and protecting the environment.

3. Discussion and conclusions

Brunei Darussalam is blessed with abundant solar energy resource but depends overwhelmingly on oil and gas for its power production. The threat posed to sustainability by greenhouse gas emission, deterioration and depletion of natural resources of fossil fuels has caused worldwide concern. This leads the researchers to consider renewable energy sources as a strategic option for alternative energy production leading to a better and more favourable environmental sustainability.

Brunei Darussalam is an oil and gas producing country and wants to use the reserves of these energy resources wisely. Despite the sustainability and environmentally friendly nature of renewable energy technologies, they look expensive compared to conventional energy sources. However, the principal costs of these technologies are the capital cost because the customers have to pay nothing towards the fuel cost. To popularise these technologies it is highly desirable to educate the public. The Government of Brunei Darussalam has taken a very wise step to introduce the generation of photovoltaic electricity in the country and connect it with the National grid. It will not only reduce the consumption of fossil fuels for power generation but also demonstrate the importance of this valuable energy source that is ample over the country to the public. The next important step to popularise the photovoltaic technology with the layman is to introduce small stand alone systems for evening food markets which are very common in the Bruneian society. It should be introduced to these markets because the energy demand for these markets is very low i.e. only for lighting and fans which can very easily be met with a standalone system of a reasonable size. This will not only reduce the fuel consumption used in generators but also provide for a clean environment. A solar diesel battery hybrid electric power system was installed in 2000 in the Temburong district which a hybrid of 2.4 kW solar array and 80 kVA diesel generator. This clearly demonstrates the Brunei Government's awareness of the importance of the utilization of solar energy for sustainable development.

In Brunei Darussalam the fate of PV technology is either to be used as a substitute or add up power facility by the Government to the national grid or as a standalone system for only small scale applications like lighting, road/street lights, traffic signals, emergency/security lights, bay lights. This is because of the fact that air-conditioning which is the basic requirement due to the climatic conditions needs a very big PV system for the individual user and the capital cost would be high and therefore be unfavourable by an ordinary customer.

Solar thermal energy could be utilized for low and medium temperature applications like solar water heaters at domestic as well as at commercial and industrial level. High temperature applications are not possible in the State because the direct component of solar radiation that can be concentrated is not available throughout the day. The global radiation is sufficient for low and medium temperature applications. Solar water heaters can be built in Brunei Darussalam to capture a substantial amount of solar thermal energy.

Passive solar architecture is another important area which can reduce the need for air-conditioning in buildings and to provide natural day light inside the building in order to cut down the use of conventional electric lighting. In order to achieve this goal, architects have to learn the art of designing such types of buildings with special shading devices and orientation.

Offshore wind has the potential to be used for green electricity generation. The wind data onshore were not accessible to be analysed for computation of power generation. The wind offshore data reveal that there is a positive potential for generation of power using onshore wind. It is recommended that this data be examined and its applicability with respect to the power generation be determined.

Ocean wave energy is another option to be studied more extensively. However, there is a positive potential for generation of electricity from tidal waves but it may not be economically viable due to the geographical location of the State.

It is highly desirable that the six landfill sites in Brunei Darussalam should be capable of producing landfill gas which is a by product of the decomposition of solid waste. This facility will not only help the proper disposal of solid waste but may also be used for power generation.

The high rainfall makes Brunei Darussalam an ideal location for the generation of hydroelectric power but due to the small area of the State it is practically not feasible to build a dam to utilize the potential of this form of energy. The running water in the rivers of Brunei Darussalam does not possess a sufficient head which could be used to generate hydroelectric power without the option of a storage dam.

Brunei Darussalam is actively participating in regional programs for energy efficiency, conservation and management. Brunei Darussalam and Japan are working together on a human capacity building program on energy efficiency and conservation. Energy auditing in Government buildings and industries has been started with the collaboration of Japan to conserve energy and to use it wisely.

The analysis of data for different sources of energy demonstrate that solar thermal and solar photovoltaic have the most potential to be used for water heating, drying crops and fruits (low and

medium temperature applications), road and street lighting, standalone systems for evening markets and photovoltaic power generator of higher rating/capacity to be added with the National grid to reduce the release of CO_2 in the environment using conventional fuels. The second important source of energy is biomass and its potential will increase as the population of the country increases. The third renewable energy source is the offshore and onshore wind power. The fourth important renewable energy source is hydroelectric power but it cannot be harnessed due to the shortage of suitable areas in the State and due to environmental concern. Ocean power (wave and tidal) has the least but positive potential that could be utilized. OTEC is not possible because the temperature gradient between the top and bottom layers of the ocean is too small to be utilized.

It is desirable that along with the introduction of renewable energy sources for power generation to increase the efficiency of the exiting power plants using conventional fossil fuels which can reduce the greenhouse gas emission. It is recommended that public would be educated to use the electrical power more wisely and effectively so that energy wastage could be minimized. The management of energy plays an important role for the sustainability and the security of energy. These precautionary measures can have a strong impact for increasing the life of fossil fuels.

It is worthwhile to seek satellite data for wind, solar and ocean waves to precisely and accurately compute the potential of renewable energies for Brunei Darussalam.

It is hoped that the potential of renewables highlighted and identified in this paper for Brunei Darussalam would provide insight to prepare the blueprints and roadmaps for the development of future energy generation strategies for the sustainable development of the State.

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